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Final Technical Report
March 1996

FREQUENCY DISCRIMINATING EM FIELD SENSOR HAVING ALL OPTICAL INTERCONNECTS

Georgia Tech Research Institute
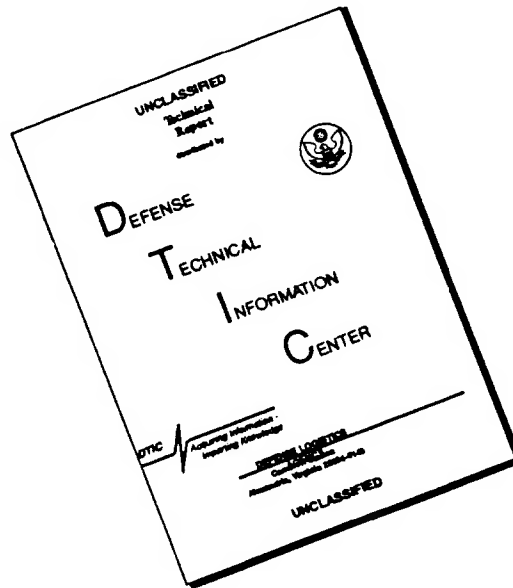
John Rohrbaugh

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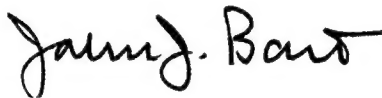
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13. ABSTRACT (Maximum 200 words)

This report describes the investigation into the feasibility of a wide bandwidth, frequency discriminating electromagnetic field sensor utilizing all optical interconnects. The sensor would be physically small with a sensitivity of 1 millivolt/meter, or better. The study included the evaluation of various RF to optical signal conversion techniques/laser diodes and their supporting hardware, and physically small, wide bandwidth antennas.

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BACKGROUND

On a recent Rome Laboratory funded effort [1], a need was identified for a small frequency discriminating electromagnetic (EM) field sensor that has only optical interconnects. The frequency discriminating EM field sensor should be capable of operating over a frequency range of 1 to 2 octaves, have a minimum sensitivity of approximately 1 millivolt per meter or less, and be physically small so that it can be located in physically restrictive areas and so that it has minimal impact on the field being monitored. Isotropic response is not necessary, although desirable. Minimally, the antenna pattern should be omni-directional or hemispheric.

A frequency discriminating EM field sensor would have numerous dual-use applications. The Federal Aviation Administration (FAA) has expressed interest in a frequency discriminating sensor to monitor signal levels on landing system frequencies. The frequency discriminating EM field sensor could also be used in International Electrotechnical Commission (IEC) susceptibility tests to verify field uniformity per the requirements of Reference 2. The IEC requires that field levels be within 6 db of 10 volts per meter over the frequency range of 30 to 1000 MHz when measured at 16 points over an area of 1.5 by 1.5 meters. Workers in the medical community have expressed an interest in a small EM emissions measurement system for use in critical care and emergency rooms. A miniature, all optical EM, field sensor would have broad applications in radiated EM emissions and susceptibility measurements.

PROGRAM OBJECTIVES

The primary objective of this effort was to investigate the feasibility of a frequency discriminating EM field sensor based on using a laser or light emitting diode (LED) at the antenna terminals as a direct RF/microwave electrical-to-optical signal converter. Temperature compensation networks, not temperature control, were evaluated as a means of extending the operating temperature range of an analog RF/microwave laser diode. Various antennas were evaluated, particularly spherical-dipoles, discones and cavity-backed spirals.

The four tasks performed on this effort were:

1.   Antenna Analysis

2.   Peltier Cooler Evaluation

3.   Temperature Compensated Laser/LED Analog RF/Microwave Data Link Development

4.   Recommendation Preparation

ANTENNA ANALYSIS

The three types of antennas that were evaluated on this effort include:

1.   Spherical-Dipole [8-10]

2.   Discone [11, 12]

3.   Cavity-Backed Spiral [12]

Spherical-dipoles and discones are preferred for their omni-directional antenna patterns and because the electronics can be mounted within each antenna without affecting the antenna patterns. Initially it was hypothesized that the bandwidth of the standard spherical-dipole could be extended by resistively loading the gap between the two hemispheres that make up the antenna. This concept proved to be untrue based on the results of tests that were performed. A balanced feed structure which is required for the spherical-dipole in order to maintain high frequency response is also difficult to manufacture. The discone can be driven single-ended rather than balanced and its physical shape results in a frequency response of nearly a decade. A cavity-backed spiral provides only hemispheric patterns but a frequency response of nearly a decade can be achieved. Further, the electronics can be mounted behind the cavity without affecting the cavity-backed spiral antenna pattern. Power dissipation in the cavity-backed spiral antenna is limited by the spiral which is a printed circuit with closely spaced conductors. These conductors can arc over and be damaged at high field levels.

For discone and cavity-backed spiral antennas having maximum dimensions of 5 inches, the low frequency cut-off would be approximately 500 MHz with an upper frequency limit of 5 GHz. The lower and upper frequency limits can be increased or decreased by appropriately scaling the dimensions of the antennas. The smallest size that can be achieved is dependent upon the size and complexity of the electronics to be incorporated into each antenna. Realistically, for surface mount electronics, the smallest dimension will be about 2 to 3 inches.

PELTIER COOLER EVALUATION

Peltier, or thermo-electric, coolers operate by sourcing or sinking current in order to maintain a device at a constant temperature of operation. Peltier coolers are typically attached to laser diodes in order to maintain the laser at a constant temperature of approximately 25 degrees Celsius (°C). A typical Peltier cooler can be operated over a ±40°C temperature range. A Peltier cooler operates like a bi-directional pair of diodes, with a nominal voltage drop of 1.2 volts. The

Peltier cooler dissipates a constant power level even if the temperature is at the nominal value, say 25 °C. For most low lasing threshold lasers, a Peltier cooler that dissipates 0.5 watt at 25 °C is usually required. At the temperature extremes of ±40°C about the 25 °C operating point, an additional 0.5 watt is dissipated in the Peltier cooler, or a dissipation of 1 watt over the ±40°C temperature range. Further, the Peltier cooler must be heat-sinked for proper operation with adequate air-flow over the heat-sink. These requirements translate to even more power for a fan and a very large size for the heat-sink and fan combination. Even though the Peltier cooler is small in size, the additional hardware required to actually make it work is not small. The power dissipation and size of a Peltier cooled laser diode limit its application in small antennas. Therefore, an alternative temperature compensation scheme must be used instead of the Peltier cooler.

LASER/LED DATA LINK DEVELOPMENT[1]

The bulk of this task was focused on developing a temperature compensated, laser based, RF/microwave analog data link. The objective was to develop a temperature compensation network to maintain the dc operating point of a laser, rather than controlling the temperature using a Peltier cooler.

Figure 1 illustrates the circuits evaluated for this task. In Figure 1a, an LED is used as the signal detection element. The LED is biased as illustrated in Figure 2a with EM fields coupled to the antenna causing the optical signal to be modulated. The LED response is approximately linear for small signal modulations around the bias point. The maximum modulation bandwidth of most high speed LEDs is approximately 200 to 300 MHz. In Figure 1b, a laser diode is used as the RF detector element and is biased just above its lasing threshold. The laser has the advantage of a much larger linear operating range than the LED and a typical frequency response in excess of 1 to 2 GHz (with greater than 18 GHz available [3]). In addition, the optical output power for the same EM field conditions should be 100 to 1000 times that of the LED. The laser-based sensor should therefore have a broader frequency range of operation, better sensitivity, and a wider dynamic range than the LED unit. The primary disadvantage in using a laser diode is its sensitivity to temperature variations. As temperature increases, the lasing threshold current will shift proportionately (output wavelength will also shift with temperature which can lead to dispersion related losses and phase shifts if the single-mode fiber optic data link is long). If a feedback circuit is used to control the dc operating point of the laser, then as temperature rises, current will also have to increase to maintain the operating point. For some diode lasers, particularly lasers that output greater that 0.5 watt optical, if heat is not removed from the laser diode junction, thermal run-away can occur. Also, as temperature increases, the slope of the laser output optical power versus current curve decreases (which is also true for an LED). Since gain decreases with temperature, there must be gain

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[1] Parts required to fully develop the circuits illustrated in Figure 1 were not received prior to the conclusion of this effort. Design plans are only provided in this section.
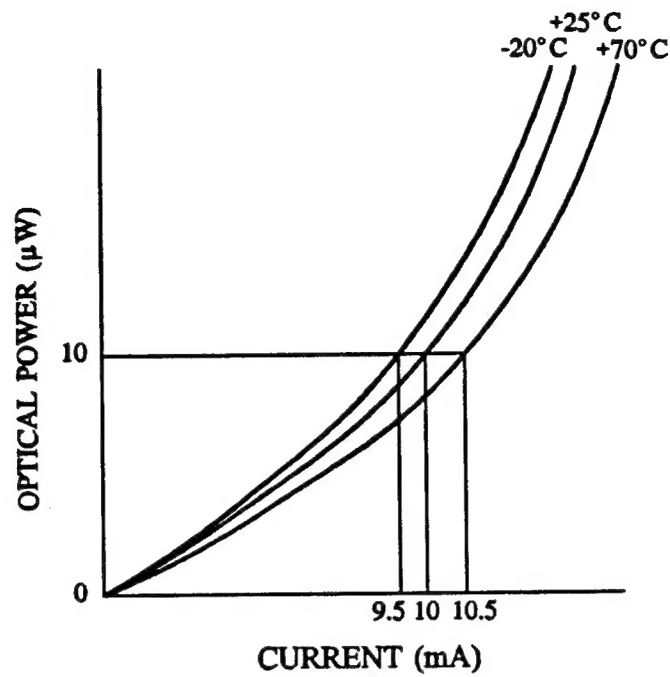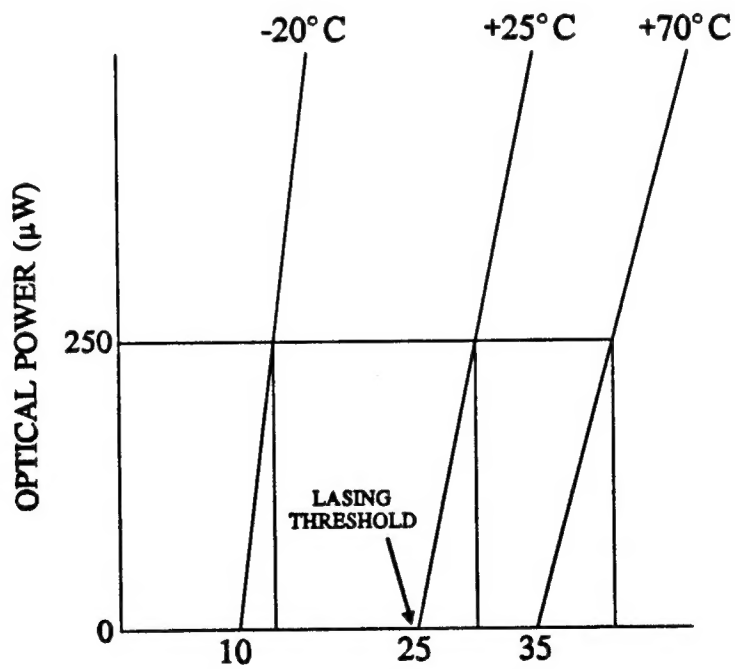
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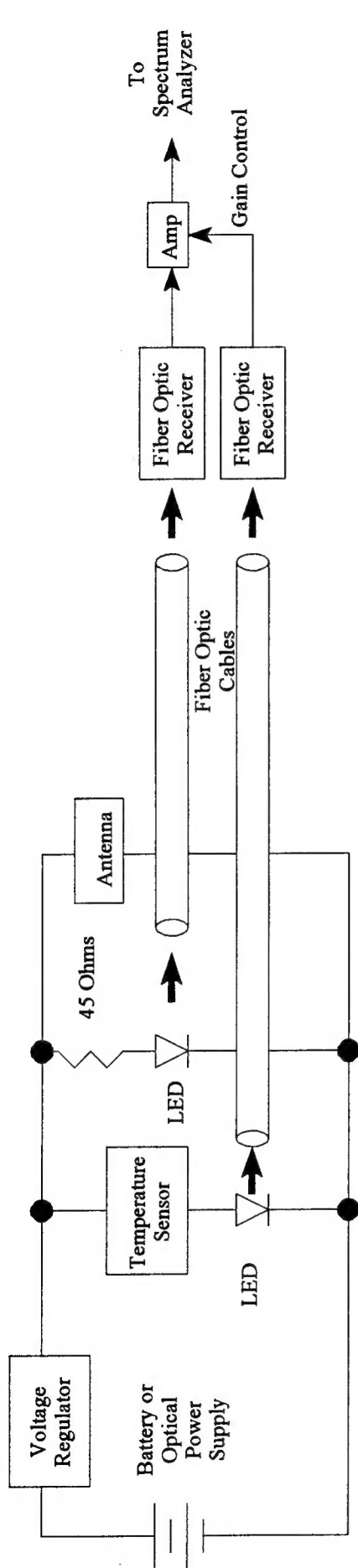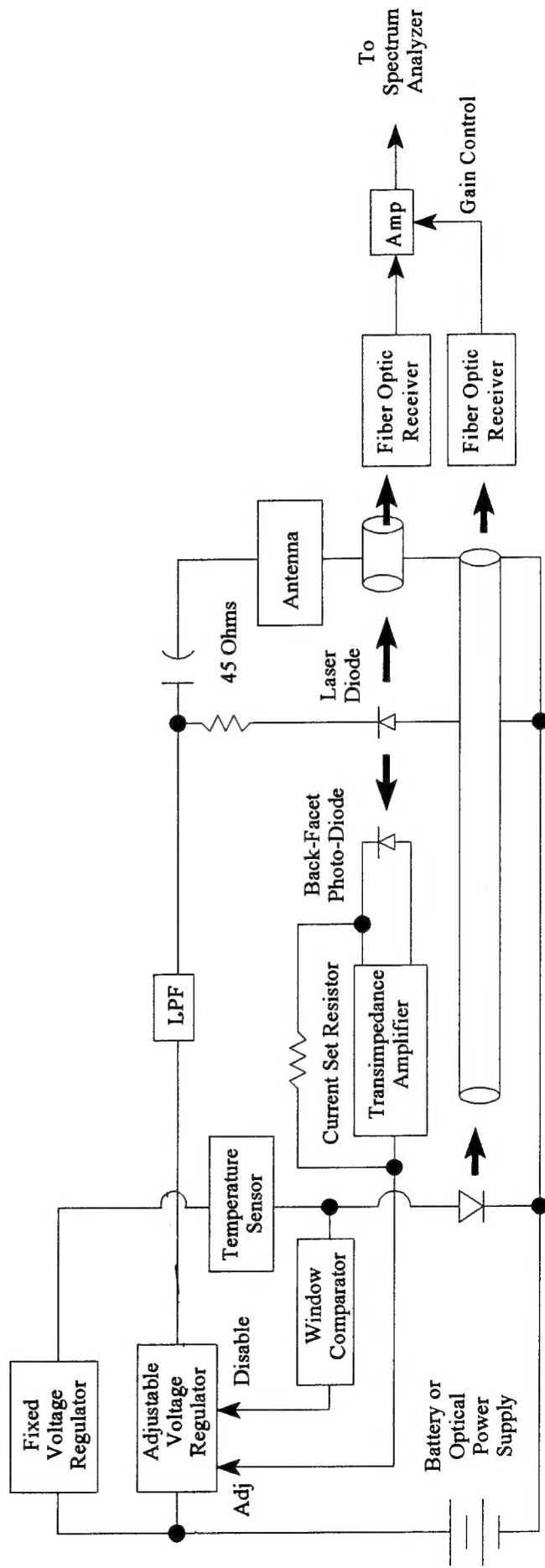
(a) LED Based Sensor.

(b) Laser Based Sensor.

Figure 1. Simplified Schematics of LED and Laser Based Sensors.

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(a) Typical LED Bias Point Shift with Temperature.

(b) Typical Laser Diode Bias Point Shift with Temperature.

Figure 2. Typical LED and Laser Diode Bias Point Shifts with Temperature.

compensation at some point in the signal transmission path. The mean time between failures of the laser is also inversely proportional to the laser operating temperature.

A number of low lasing threshold diode lasers are available that are thermally stable if operated over manufacturer specified temperature ranges and current levels. Figure 3 presents the data on a laser diode from AMP/Lytel [4] that has a lasing threshold between 5 and 25 mA over the temperature range of -40 to +85 C° and that can be modulated to current levels of 80 mA without thermal runaway. This laser diode has a minimum 3-db modulation bandwidth of 1 GHz, typically 1.5 GHz.[2] The AMP/Lytel laser diode operates at a nominal wavelength of 1310 nm.

The planned control circuit for the AMP/Lytel laser is shown in Figure 1b. A back-facet PIN photo-diode (incorporated into the laser package) is used to form a bias control loop. A linear feed-back amplifier is used to maintain the output of the optical back diode at a constant signal level by varying the bias current of the laser diode. The laser bias current is adjusted by controlling the output voltage of a programmable voltage regulator. The laser back-facet optical power leakage is generally 10 to 100 times lower than the forward optical power level and is constant with temperature. A control loop can be constructed using a PIN photo-diode at the back facet, a transimpedance amplifier and an adjustable regulator, as shown in Figure 1b. In this case, since the laser that was purchased has a grounded anode, a negative adjustable voltage regulator is used as the controlling element. The negative regulator operates by integrating about a reference voltage of -1.2 volts. If the optical power drops then the regulator compensates by reducing the output voltage (more negative) in order to maintain the transimpedance amplifier output voltage at -1.2 volts. Similarly, if the optical output power increases, the regulator increases the output voltage (less negative) in order to maintain the transimpedance amplifier output voltage at -1.2 volts. Such a control circuit is unnecessary for the LED version shown in Figure 1a since the bias point does not shift significantly along the current axis with temperature. Gain can be adjusted for changes in temperature by recording the temperature, transmitting this information over a separate fiber optic data link and using the recovered "temperature signal" to control the gain of the final output amplifier. The temperature signal can also be monitored to determine when the laser is operating outside the -40 to +85 °C temperature range. A simple window comparator circuit within the sensor can be used to shut-down the sensor power supply in the event of under- or over-temperature conditions.

The initial bias current set point can be programmed by adjusting the transimpedance amplifier current-to-voltage gain, i.e., by changing the feedback resistor value. The dynamic range of the regulator is sufficient to vary the current over the desired range of approximately 20 to 70 mA once the initial bias current level is set. By changing the transimpedance amplifier gain instead of the laser load resistor, the RF impedance of the laser diode circuit can be maintained at a constant level, in this case approximately 50 ohms (the laser RF impedance is always less than 5 ohms and does vary, but the maximum error is less than a few percent when added to the 45 ohm fixed resistor value):

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[2] A temperature stable, low lasing threshold laser described in [3] has a 3-db bandwidth in excess of 18 GHz. The AMP/Lytel laser is discussed because the objective of this effort was only to demonstrate concepts using low cost components.

Features

- 1300 nm wavelength
- –40°C to 85°C operating temperature
- Hermetically sealed
- High speed (1 GB/s)
- InGaAs monitor detector
- Four-lead package
- Each unit serialized

The AMP MQW wide temperature coolerless Laser module is available in both a pigtailed package and as a connectorized component. The high temperature laser module incorporates a 1300 nm InGaAsP laser diode and InGaAs monitor photodetector for stable tracking over temperature. The electro-optical components are hermetically sealed in a TO-5.6 mm can and are laser welded to an advanced optical assembly. Every device is biased and aged to ensure the highest degree of reliability and stability.

The AMP Laser module is ideal for most short and medium distance digital loop transmission applications over singlemode fiber. Laser modules are processed to comply with the intent of Bellcore advisory TA-TSY-000983.

Each unit is temperature cycled and burned in.

Data supplied with each unit includes threshold current, slope efficiency, monitor current and wavelength. A serial number is used for traceability.

For additional information on product qualification, reference Product Specification 108-55006.
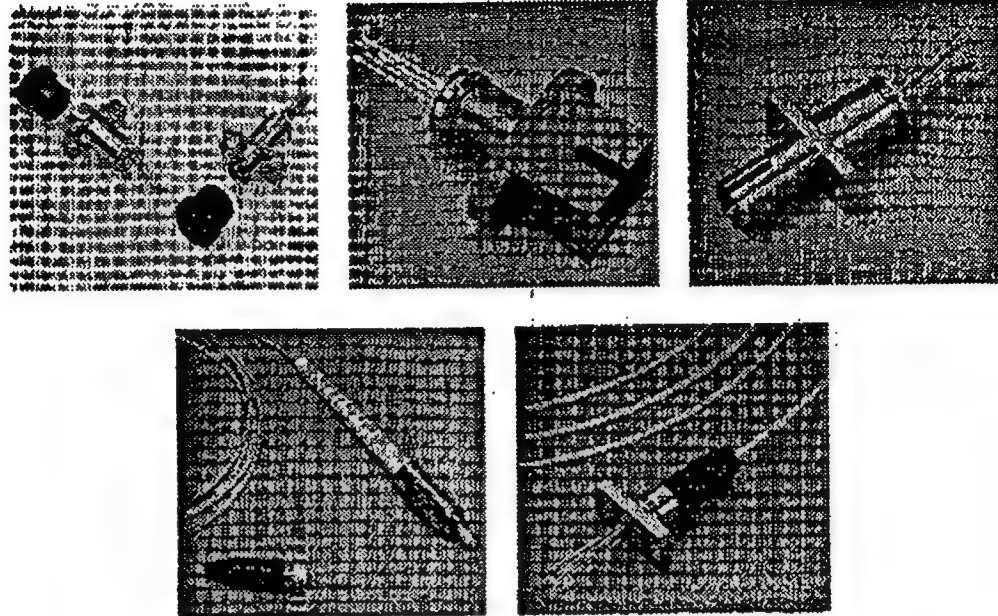
Specifications: 25°C Unless Otherwise Stated

Parameter	Symbol	Test Conditions	Units	Min.	Typ.	Max.
Threshold current	I_{th}	—	mA	—	9	20
Forward voltage	V_F	P_o	V	—	1.2	1.5
Forward current	I_F	P_o	mA	—	30	50
–4 Optical output power	P_o	—	mW	—	0.1	—
–1 Optical output power	P_o	—	mW	—	0.2	—
–2 Optical output power	P_o	—	mW	—	0.5	—
–3 Optical output power	P_o	—	mW	—	1.0	—
Center wavelength	λ	P_o –40 to 85°C	nm	1290	1310	1330
Spectral width RMS	$\Delta\lambda$	P_o	nm	—	2.0	—
Rise/fall times	T_R, T_F	10–90%	ns	—	0.4	—
–4 Differential efficiency	ξ	P_o	mA/mW	.008	—	—
–1 Differential efficiency	ξ	P_o	mA/mW	.01	—	—
–2 Differential efficiency	ξ	P_o	mA/mW	.02	—	—
–3 Differential efficiency	ξ	P_o	mA/mW	.05	—	—
Tracking error	E_r	–40 to 85°C	dB	—	±0.5	—
Monitor photocurrent	I_{mon}	P_o	mA	0.1	—	0.7
Photodiode cap.	C_t	—	pF	—	15	—

Absolute Maximum Rating

	Symbol	Min.	Typ.	Max.	Units
Forward current	I_F	—	—	80	mA
Reverse voltage	V_R	—	—	2	V
Operating temp.	T_C	–40	—	85	°C
Storage temp.	T_{STG}	–40	—	85	°C

Figure 3. AMP/Lytel Laser Specifications.

Loop control filters (LPF in Figure 1b) can be used to prevent RF signals from affecting the laser bias control circuit. The filter is important to prevent RF leakage into the control circuit non-linearities from being rectified and added to or subtracted from the laser bias signals.

The fiber optic receiver that was purchased for use in the demonstration unit was the PDC 2200-24 pin diode receiver from BT&D (now owned by Hewlett-Packard) [5]. This receiver has a 3-db bandwidth of 3 GHz. (BT&D/HP manufactures a PIN diode fiber optic receiver that has 18 GHz 3-db bandwidth that could be used in conjunction with the 18 GHz laser in [3].) Single-mode fiber optic cable would be used between the laser diode and pin diode receiver. An Avantek MSA-0635 amplifier [6] is planned for use as the final amplifier before the spectrum analyzer.

The demonstration unit was designed to operate on battery power; however, the ultimate goal is to develop a unit that can be operated using an optical power cell. The circuits shown in Figure 2b can be operated at between 2 and 5 volts if the laser/LED operating point is limited to a few tens of milliamps. For a maximum dc operating point of 45 mA to maintain approximately 0.6 mW optical output power and a voltage level of 5 volts, the total power dissipation is less than 225 mW. The temperature sensor and voltage feedback circuits can be operated at less than 50 mW for a total power dissipation of less than 275 mW. Optical power cells from Photonic Power Systems [7] can be obtained that provide in excess of 1.5 W electrical power at input optical power levels of 3 W. The Photonic Power Systems cells are 50% efficient at a wavelength of 860 nm and have the added feature of being transparent at 1310 nm which is the operating wavelength of many high bandwidth LEDs and low lasing threshold laser diodes. If a wavelength division multiplexer is used at the power source/signal receiver end of the fiber optic link, then a single fiber optic cable can be used to route optical power to the sensor and the RF/microwave signal from the sensor. No batteries are required in the sensor and the circuit could be miniaturized substantially using an optical power cell. A second fiber is used to route the temperature signal but could be packaged into a common fiber bundle to minimize size.

CONCLUSIONS AND RECOMMENDATIONS

Parts which were required to allow the full-prototype sensor to be developed and tested were not received prior to the conclusion of this effort. Preliminary measurements of the laser control circuit indicate it should work as designed. The main recommendation from this effort is to continue the development and testing of this field sensor concept using the already purchased parts. Additional recommendations for follow-on activities that should be undertaken include:

1. Identify specific applications that could benefit from use of a laser based analog data link. Key criteria should be identifying the minimum operating frequency range of the link, the signal dynamic range, the degree of required signal linearity, the operating temperature range (which determines if a Peltier cooler must be used and the required power dissipation,

since the Peltier cooler will require more power than the remaining circuitry), the degree of miniaturization required, the link calibration techniques that can be applied, the sensor operation time (which dictates battery operation limits and ultimate size if optical power cannot be incorporated), and acceptable cost. Currently known applications require operation over only one to 1½ frequency decade, with a unit capable of operating from approximately 100 MHz to 2 GHz covering most applications. Incorporation within a discone antenna or behind a cavity backed spiral antenna would also serve adequately in most applications. Miniaturization of the receiver and optical power source is not required for most applications and a non-miniaturized receiver can be produced at low cost to demonstrate the concept.
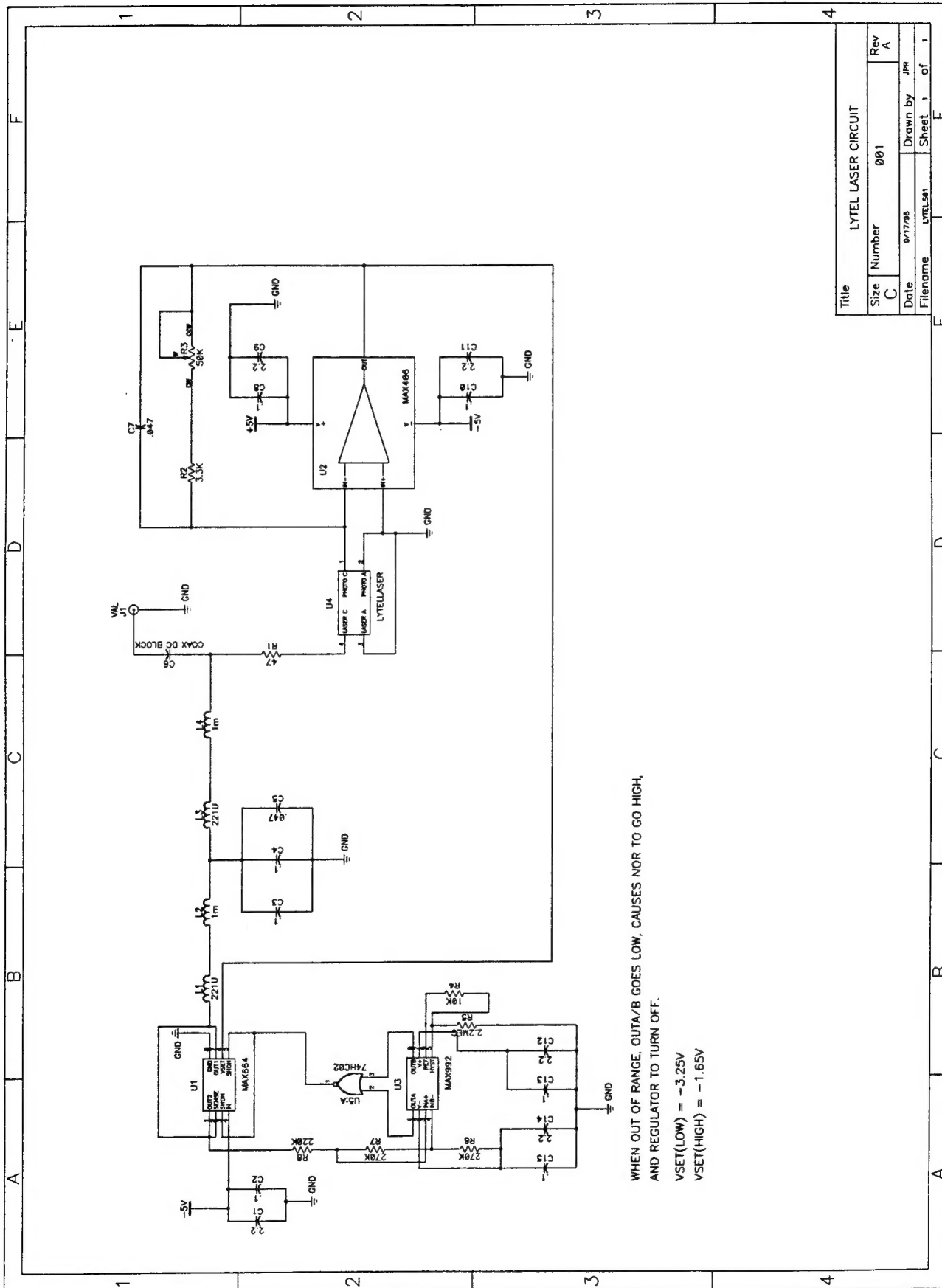
2. After the concept has been demonstrated, RL should seek to miniaturize the sensor electronics, reduce sensor power consumption, develop novel data link calibration and temperature compensation techniques, broaden the sensor operating bandwidth, reduce the size and power consumption of the receiver electronics, incorporate sophisticated microcontrollers within the receiver for custom applications, and design to operate over more stringent temperature, shock and other environment extremes. Any improvement activity should address a specific application, and only those elements critical to the application should be improved to reduce cost and risk to the government.

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APPENDIX: Detailed Schematic of Planned Sensor

WHEN OUT OF RANGE, OUTA/B GOES LOW, CAUSES NOR TO GO HIGH,
AND REGULATOR TO TURN OFF.

VSET(LOW) = -3.25V
VSET(HIGH) = -1.65V

Title	LYTEL LASER CIRCUIT		
Size	Number		Rev
C	001		A
Date	9/17/95	Drawn by	JPR
Filename	LYTEL.S01	Sheet 1 of 1	

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